Aquifers of the Denver Basin, Colorado[1]

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ABSTRACT

Development of the Denver Basin for water supply has been ongoing since the late 1800s. The Denver Basin aquifer system consists of the water-yielding strata of Tertiary and Cretaceous sedimentary rocks within four overlying formations. The four statutory aquifers contained in these formations are named the Dawson, Denver, Arapahoe, and Laramie-Fox Hills. For water rights administrative purposes, the outcrop/subcrop of the Laramie-Fox Hills aquifer defines the margins of the Basin. Initial estimates of the total recoverable groundwater reserves in storage, under this 6700-mi^2 area, were 295 million acre-ft. Recent geologic evidence indicates that the aquifers are very heterogeneous and their composition varies significantly with distance from the source area of the sediments. As a result, available recoverable reserves may be one-third less than previously estimated. There is no legal protection for pressure levels in the aquifer, and water managers are becoming increasingly concerned about the rapid water level declines (30 ft/yr). Approximately 33,700 wells of record have been completed in the sedimentary rock aquifers of the Denver Basin for municipal, industrial, agricultural, and domestic uses.

INTRODUCTION

Once the driving force operating the elevators in the Brown Palace Hotel and running the bellows for the Trinity Church organ, the underground waters of the Denver Basin have been put to beneficial use since the late 1800s (Van Diest, 1891). To further the understanding of this resource, evaluations of the geology and hydrology of the formations in the Basin soon followed (Cross et al., 1884; Emmons et al., 1896). By the early 1980s, more than 1,800 reports dealing with the geology and hydrology of the Denver Basin had been published (Robson, 1987). The importance of the Denver Basin, as a major bedrock aquifer system, in the State of Colorado for supplementing limited surface water resources is well documented (Topper et al., 2003).

This special issue of *The Mountain Geologist* focuses on this tremendous and controversial groundwater reservoir. Invited papers contained herein present the geology and hydrology of the Denver Basin, the regulatory framework established for the administration of water rights, structural and stratigraphic relationships influencing the basin's hydrogeology, recharge/discharge considerations, and innovative technologies available to optimize groundwater withdrawals. This introductory paper establishes the framework for understanding the hydrogeology of the aquifers in the Denver Basin and the demands placed on this resource. Much of the information presented here is derived from the Denver Basin chapter of the recently published *Groundwater Atlas of Colorado* by the Colorado Geological Survey (Topper et al., 2003). That atlas is a comprehensive, map-based publication that presents the location, geography, geology, water quality, and hydrologic characteristics of the state's major aquifers in an artistic, understandable manner.

LOCATION AND GEOLOGIC SETTING

The Denver Basin is a structural sedimentary basin that underlies the Denver metropolitan area within the Great Plains physiographic province. The Basin is rich in mineral fuels, with active production of oil and gas, and is a historic coal producer. It is also an important non-renewable source of groundwater for municipal, industrial, agricultural, and domestic uses. This layered, multi-aquifer system is recognized nationally as a major aquifer from a water resource perspective. The administrative groundwater portion of the Basin, for water rights considerations, underlies a 6700-mi^2 area extending into Weld County on the north; El Paso County on the south; Jefferson County on the west; and the eastern parts of Adams, Arapahoe, and Elbert counties on the east (Fig. 1). This corresponds to the area of outcrop/subcrop of the Laramie-Fox Hills aquifer south of the Greeley Arch.

The 8-county Denver metropolitan area contains 56% of Colorado's population, slightly over 2.4 million people according to the 2000 census. In addition to housing a large population, this area represents the largest commercial and industrial region in the state. Major industries include agriculture, communications, oil and gas, utilities, and transportation. Faced with a paucity of surface-water supplies and accelerated urban growth, water districts and water suppliers are relying on and extensively developing the Denver Basin aquifers as both primary and supplemental sources of water supply.

The Denver Basin aquifer system consists of water-yielding strata (predominantly sandstones and siltstones) in Tertiary and Cretaceous sedimentary rocks. The northern part of the Denver Basin aquifer system underlies the alluvial aquifer of the South Platte River, and is hydraulically connected to that unconsolidated aquifer over part of the area. In descending order, the geologic formations that contain the Denver Basin aquifers are Tertiary and Cretaceous sandstone, conglomerate, and shale of the Dawson, Denver, Arapahoe, Laramie, and Fox Hills formations (Romero, 1976). The four statutory aquifers contained in these formations are named the Dawson, Denver, Arapahoe, and Laramie-Fox Hills (Table 1). Underlying the Fox Hills sandstone is as much as 7000 ft of nearly impermeable shale known as the Pierre Shale. Although the Denver structural basin extends north into Wyoming and contains permeable Cretaceous rocks, they are little utilized as a source of water north of Greeley (Fig. 2).

In cross-section, the Denver Basin's asymmetrical bowl shape is expressed by low-angle dips of the uppermost rock units along the northern, eastern, and southern margins, and high-angle dips along the western margin. The outcrop area of each successively deeper aquifer becomes larger while maintaining the Basin's overall kidney shape. The center of the basin lies just west of the town of Parker, where the Laramie-Fox Hills aquifer is approximately 3000 ft deep. Economic considerations have generally limited water well depths to 2500 ft.

HYDROGEOLOGIC UNITS

In a cooperative effort, scientists with the U.S. Geological Survey (USGS) and the Colorado Division of Water Resources (CDWR) have conducted some of the most detailed investigations available of this aquifer system culminating in the publication of a USGS Hydrogeologic Atlas series: HA-643 (Dawson Aquifer); HA-646 (Denver Aquifer); HA-647 (Arapahoe Aquifer); and HA-650 (Laramie-Fox Hills Aquifer) in 1981 (Robson and Romero, 1981a,b; Robson et al., 1981a,b). This series of atlases was expanded upon and refined as a consequence of the passage of Colorado Senate Bill 5, which required the promulgation of rules and regulations applying exclusively to the withdrawal of groundwater from the Denver Basin (VanSlyke et al., 1988). Robson (1987) prepared a quantitative water resource appraisal of the bedrock aquifers in the Denver Basin that included the first groundwater flow model analysis.

Table 1 provides a summary of both the geologic and hydrologic characteristics of the Denver Basin aquifer system. A brief synopsis of the four main aquifer units follows. The Dawson aquifer, the shallowest aquifer in the basin, is at or near the land surface throughout its entire areal extent. It covers an area of approximately 1400 mi^2. The Dawson aquifer consists primarily of conglomeratic, coarse-grained arkosic sandstones with minor amounts of interbedded clay and clay shale (VanSlyke, 2001). The Dawson Formation ranges in thickness from a few feet to 1200 ft. The saturated portion of the aquifer may be up to 400 ft thick in the deeper portion of the basin (Fig. 3).

The Denver aquifer underlies an area of approximately 3500 mi^2. The sediments comprising the aquifer consist of interbedded shale, claystone, siltstone, lignitic coals, and sandstone lenses. The aquifer ranges in thickness from 800 to 1000 ft. Because of the interbedded shale and claystone, the thickness of saturated water yielding materials generally ranges from 100 to 350 ft (Fig. 3). Distinguishing characteristics of this formation include its olive, green-gray, and brown color; the presence of organic matter and coal; and the fine-grained and discontinuous nature of the sandstone lenses.

The Arapahoe aquifer underlies an area of approximately 4700 mi^2 and consists of an interbedded sequence of conglomerate, sandstone, siltstone, and shale. The formation is 400 to 700 ft thick and is up to 2200 ft deep in the center of the Basin. The saturated thickness of the water-yielding materials in the aquifer ranges from 0 along the margins to a maximum of 400 ft in the basin center (Fig. 3). The Arapahoe aquifer is the most prolific of the Denver Basin aquifers, and it is extensively used as a municipal water supply.

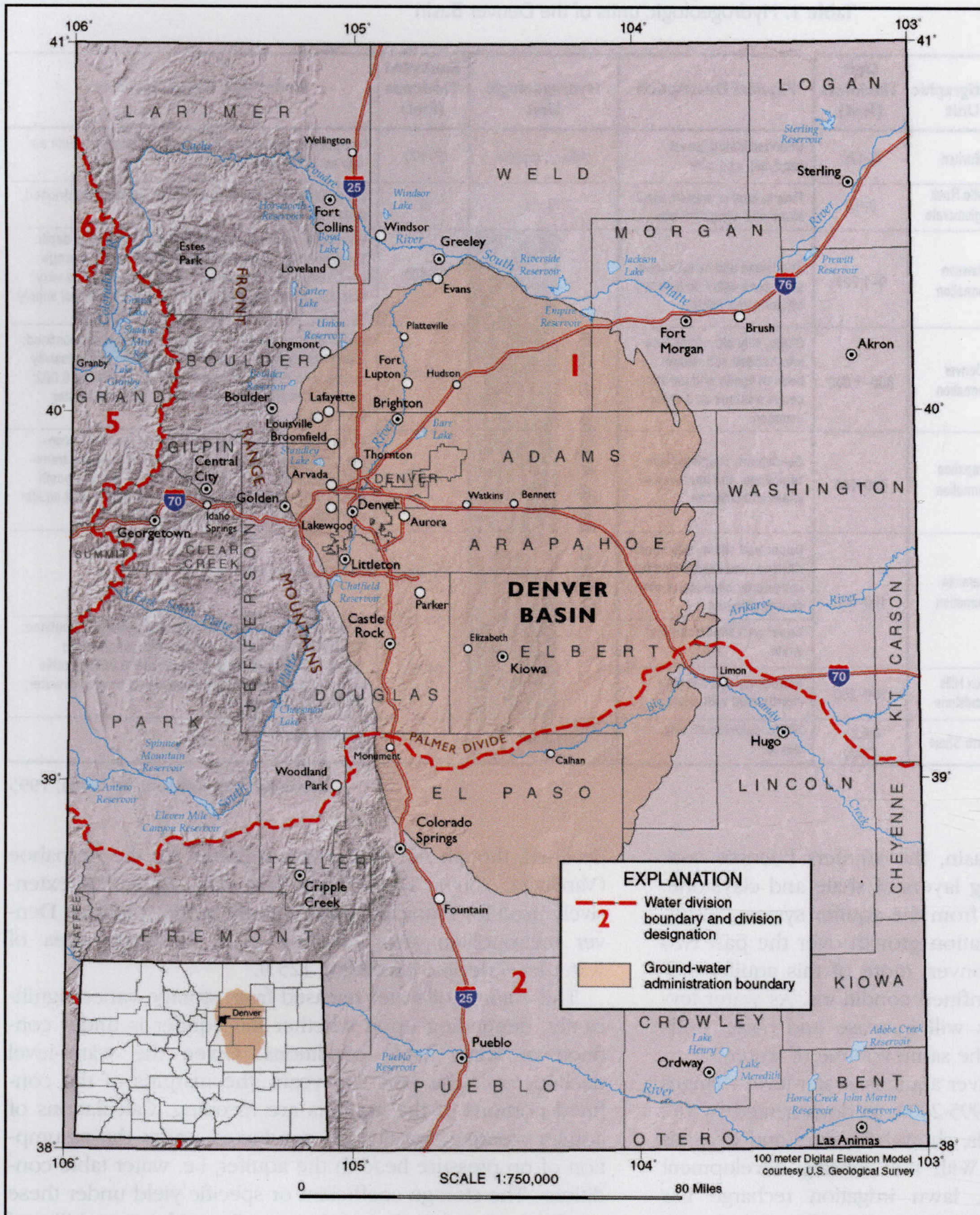

Figure 1. Location of the Denver Basin (groundwater administration boundary)

The Arapahoe aquifer is underlain by up to 400 ft of shale with minor beds of coal, sandstone, and siltstone known as the Laramie Formation. In places, the basal portion of this formation contains relatively thick fluvial sandstone units. In conjunction with the near-shore to beach facies Fox Hills sandstone, these sandstones comprise what is known as the Laramie-Fox Hills aquifer. This aquifer underlies the entire 6700-mi^2 area of the Basin and marks the areal extent of the commercially economic groundwater development for the Denver Basin. The aquifer is up to 350 ft thick with 40 to 60% being fine- to medium-grained sandstones. The total thickness of water yielding materials rarely exceeds 200 ft (Fig. 3).

WATER LEVELS AND WATER STORAGE

In their respective outcrop areas, the Denver Basin aquifers are under water-table (unconfined) conditions. In

Table 1. Hydrogeologic units of the Denver Basin

Era	System	Series	Stratigraphic Unit	Unit Thickness (feet)	Physical Description	Hydrogeologic Unit	Saturated Thickness (feet)	Hydrologic Characteristics
Cenozoic	Quaternary	Holocene Pleistocene	Alluvium	0–125	Unconsolidated gravel, sand, silt, and clay	Alluvial aquifer	0–100	Unconfined, shallow aquifer; very permeable; yields as high as 3,000 gpm
	Tertiary	Oligocene	Castle Rock Conglomerate	0–50	Fine to coarse arkosic sandstone and conglomerate	None	0	Exposed in cliffs; forms cap rock on buttes; well drained, does not yield water
		Eocene Paleocene	Dawson Formation	0–1,200	Sandstone and conglomeratic sandstone with interbedded siltstone and shale	Denver Basin Aquifer System: Dawson aquifer	0–400	Water table aquifer in shallow units, and confined at depth. Transmissivity ranges from 500–5,000 gpd/ft; storage coefficients range from 0.002–0.009; specific yields vary from 15–25%; domestic water source and municipal supply for Castle Rock; may yield as much as 300 gpm
Mesozoic	Cretaceous	Upper Cretaceous	Denver Formation	800–1,000	Shale, silty claystone, and interbedded sandstone; beds of lignite and carbonaceous siltstone and shale common	Denver aquifer	0–350	Water table aquifer near outcrop area; generally confined; least permeable of Denver Basin aquifers; transmissivity ranges from 250–2,000 gpd/ft; storage coefficient 0.002; specific yield 10–17%; domestic and municipal water source; yields up to 200 gpm
			Arapahoe Formation	400–700	Sandstone, conglomeratic sandstone, and interbedded shale and siltstone	Arapahoe aquifer	0–400	Water table aquifer near outcrop area; generally confined; most permeable of Denver Basin aquifers; transmissivity ranges from 500–5,000 gpd/ft; storage coefficient 0.002–0.009; specific yield 10–25%; principal aquifer source for municipal water; yields up to 700 gpm
			Laramie Formation	100–600	Upper part shale, silty shale, siltstone, and interbedded fine sandstone; bituminous coal seams common	Laramie confining unit	0–400	Shale is impermeable
					Lower part sandstone and shale	Laramie Fox-Hills aquifer	0–250	Water table aquifer near outcrop area; generally confined; moderately permeable; transmissivity ranges from 1,000–7,000 gpd/ft; storage coefficient 0.001; specific yield 15–20%; source for domestic and municipal water; yields up to 350 gpm
			Fox Hills Sandstone	100–200	Sandstone and siltstone interbedded with shale			
			Pierre Shale	4,500–7,000	Shale, calcareous, silty, and dense.	Confining unit	0	Impermeable

Modified from Robson and Banta, 1995

the deeper parts of the Basin, the aquifers become confined due to the intervening layers of shale and claystone. The increased withdrawals from the aquifer system, resulting from accelerated population growth over the past two decades, is beginning to convert more of this aquifer system from confined to unconfined conditions. As water levels decline, pumping costs will increase and more wells will be required to extract the same volume of water.

For the Dawson and Denver aquifers, water-level changes over the five-year period, 1995-2000, as documented by the CDWR from select key wells, show both rises and declines depending upon location. With the housing development boom of the last decade, lawn irrigation recharge has become a significant recharge process for parts of these two aquifers. The picture for the dominant municipal water supply aquifers, the Arapahoe and Laramie-Fox Hills, however is not so stagnant. Over the past ten years, water levels have declined throughout the Arapahoe aquifer. Extensive development in the south metropolitan area of northern Douglas and eastern Arapahoe counties has resulted in declines from 100 to almost 300 ft (VanSlyke, 2000). With declines of up to 30 ft/yr, the future prospects for this aquifer are of great concern to water managers. Likewise, over the past 10 years water levels in the Laramie-Fox Hills aquifer have also declined, though not at the rates reported for the Arapahoe (VanSlyke, 2000). The Laramie-Fox Hills aquifer is extensively used for municipal water supply in the southeast Denver metropolitan area, resulting in a substantial area of water-level decline exceeding 125 ft.

The volume of water released from storage varies significantly, depending upon whether the aquifer is under confined or water table conditions. Given the water-level declines over the past 20+ years, the margins of the confined portions of the aquifers are receding. Calculations of aquifer storage capacity are conducted under the assumption of no pressure head in the aquifer, i.e. water table conditions. The storage coefficient or specific yield under these conditions is a function of the porosity and permeability of the material. Robson (1987) estimated that about 467 million acre-ft of water are stored in the Denver Basin aquifer system. The actual amount of recoverable water is significantly less due to physical and practical limitations. In 1985, as a part of the research done to support Senate Bill 5, the Colorado Division of Water Resources estimated that approximately 295 million acre-ft of water was potentially recoverable (Table 2). The 295 million acre-ft represents about 1200 times the volume of Dillon Reservoir. This recoverable reserve represents a theoretical upper limit,

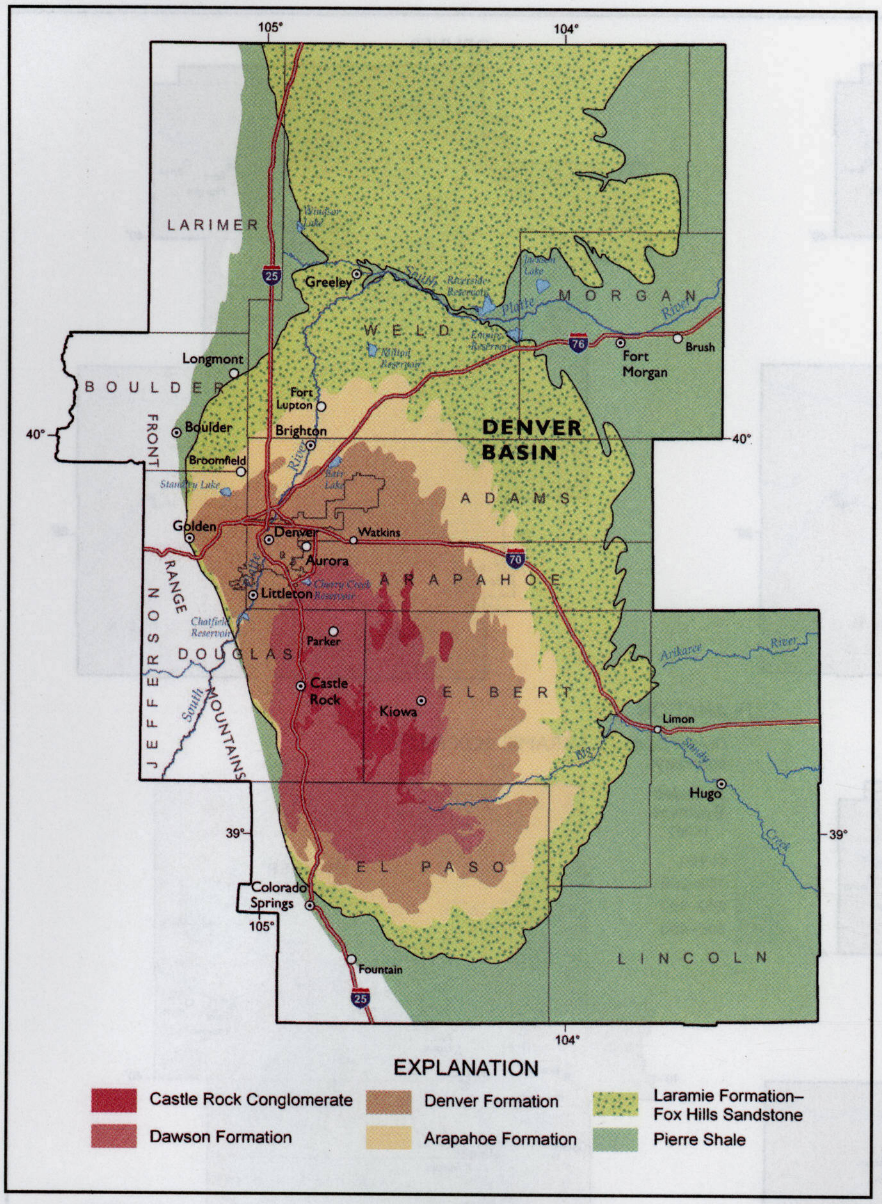

Figure 2. Bedrock geology of the Denver Basin.

Modified from Denver Museum of Nature and Science, 1999

however, as wells are mechanically incapable of completely draining an aquifer and economic considerations (costs of pumping) will limit actual recoverable amounts.

In 1987 and 1988 a deep test well was drilled in Castle Pines, and in 1999 a similar well was drilled near the town of Kiowa. These wells were drilled by public agencies to further the existing knowledge of the geology and hydrogeology of the Denver Basin aquifer system. Both wells were continuously cored throughout the aquifer sequence. Aquifer properties ascertained from the Castle Pines and Kiowa core holes suggest that the aquifers are very heterogeneous and vary significantly with distance from the source area of the sediments comprising the aquifer. The new core hole data suggests that the quantity of recoverable water stored within the Denver Basin may be one-third less than previously estimated by Senate Bill 5 (Table 2).

GROUNDWATER WITHDRAWALS

Groundwater withdrawals within the Denver Basin aquifers have a long history. The USGS reported that during 1985, total withdrawals from the Denver Basin aquifers were 36,000 acre-ft from approximately 12,000 wells (Robson and Banta, 1995). During that year, 53% of the water was used for public supply and 34% was used for agriculture.

As of February 2001, approximately 33,700 wells of record have been completed in the sedimentary rock

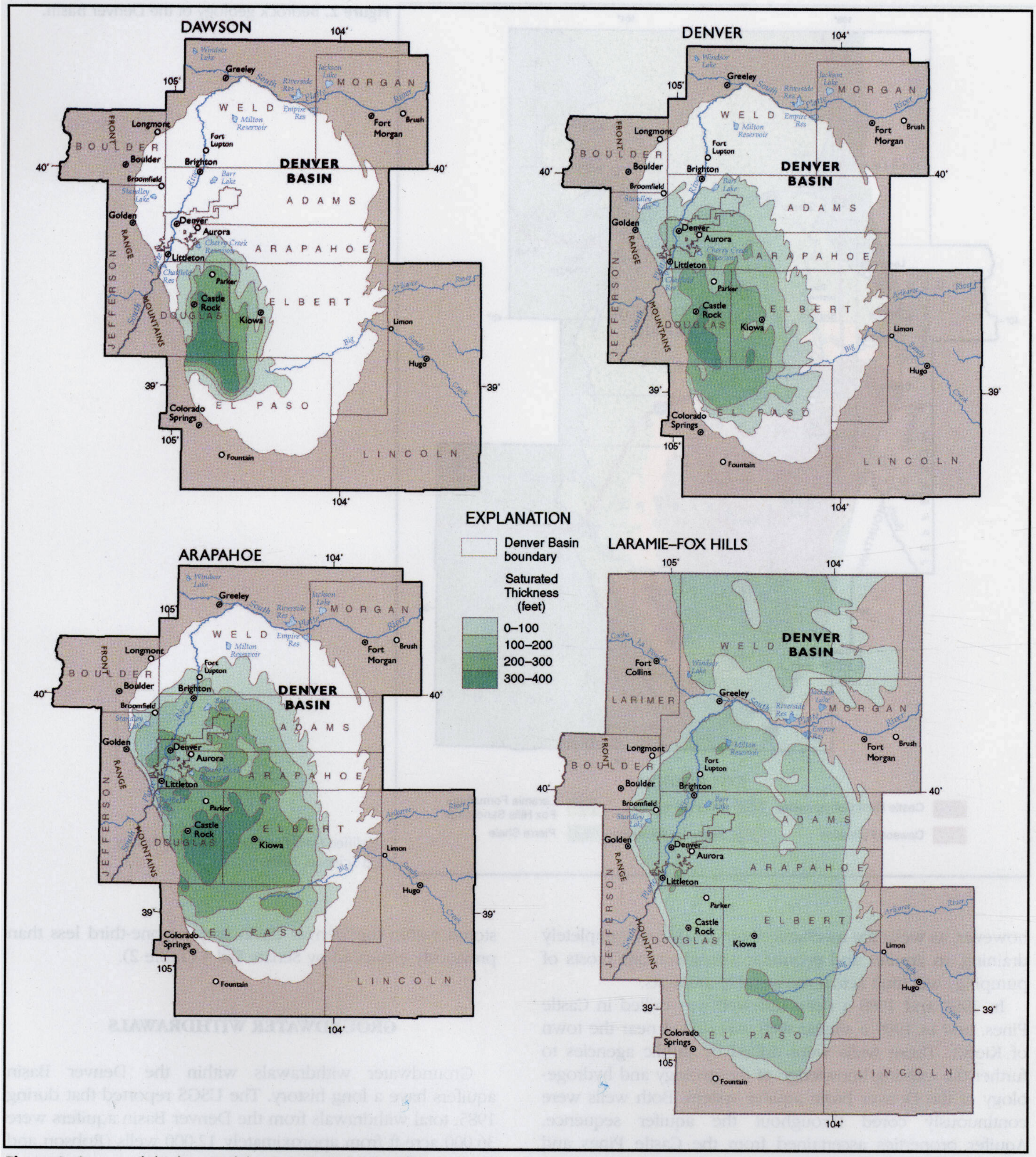

Figure 3. Saturated thickness of the Denver Basin aquifers. Modified from Robson and Banta, 1995

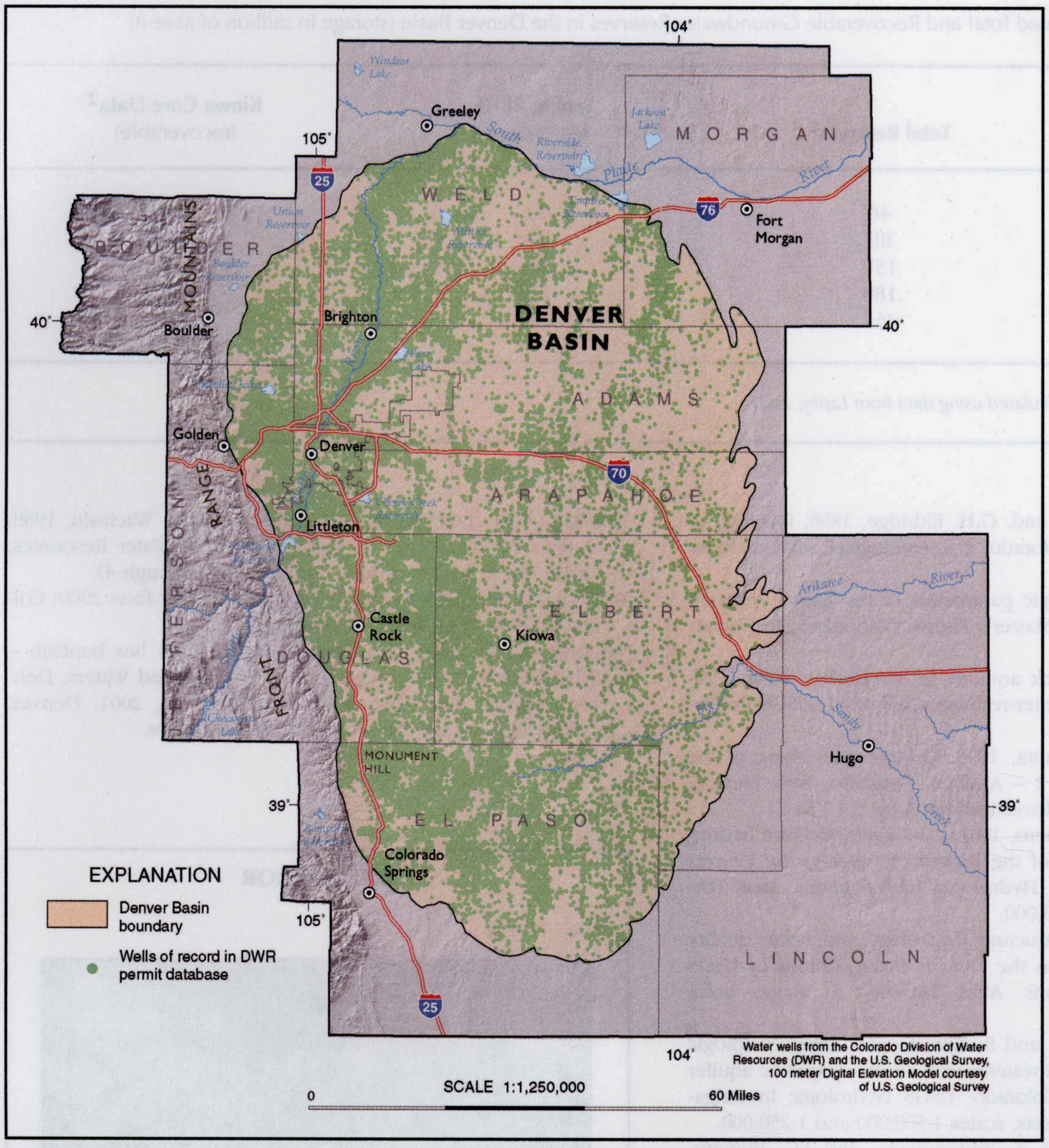

Figure 4. Denver Basin water well distribution map.

aquifers of the Denver Basin. This is almost a three-fold increase in wells penetrating the Denver Basin aquifers since 1985. The distribution of these wells is shown in Figure 4. Total current withdrawals for the Denver Basin are not available. Available county information indicates that in 1995 nearly 445,000 acre-ft of groundwater was withdrawn in Adams, Arapahoe, Denver, Douglas, and Elbert counties, which lie almost entirely in the Basin (Solley et al., 1998). The county withdrawal volumes do not distinguish between alluvial wells and the deeper aquifers and, therefore, cannot be compared directly to the 1985 volumes cited above. Nevertheless, the sheer size of the annual withdrawal volume appears to indicate a significant acceleration in groundwater withdrawal from the Denver Basin aquifers between 1985 and 1995.

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Table 2. Estimated Total and Recoverable Groundwater Reserves in the Denver Basin (storage in million of acre-ft)

Aquifer	Total Reserves[1]	Senate Bill 5 (recoverable)	Kiowa Core Data[2] (recoverable)
Dawson	48	32	22
Denver	89	71	50
Arapahoe	150	90	63
Laramie-Fox Hills	180	102	71
Total	467	295	206

[1] from Robson, 1987; [2] calculated using data from Lapey, 2001

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